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STRESS-CORROSION CRACKING TESTS ON A LINE-PIPE STEEL

by
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ABSTRACT

Stress-corrosion cracking (SCC) tests have been performed on small two-point-loaded bent strips of a controlled-rolled line-pipe steel with a yield strength of 448 MPa (65 ksi). The three test solutions used were those developed elsewhere for laboratory studies of the SCC phenomenon in buried gas transmission pipelines.

In 20% NH_4NO_3 solution, SCC was observed in freely corroding specimens at temperatures from 30 to 101.5°C (86 to 215°F). In 33% NaOH solution at a potential of -0.96 V SCE, SCC was observed for specimens which had been strained in the solution, to a minimum temperature of 60°C (140°F). In tests in $\underline{N}$ Na_2CO_3-$\underline{N}$ $NaHCO_3$ solution, potentials were altered according to the temperature in the range of -0.55 to -0.67 V SCE. For specimens strained in the solution, SCC was observed at a minimum temperature of 22°C (72°F).

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INTRODUCTION

In 1965, an underground gas transmission pipeline in the U.S.A. failed by a mechanism subsequently defined as stress-corrosion cracking (SCC)*. This failure was at first regarded as unique, and recurrence was not expected. However, since that time a number of additional SCC failures have been reported. The Proceedings of the Fifth Symposium on Line-Pipe Research, held Nov. 1974 [1], make it clear that SCC of gas transmission pipelines constitutes an increasingly serious and widespread problem to which there is at present no simple solution.

R.L. Wenk [2] has described the characteristics of the SCC observed in pipelines in some detail. At the time of his report, 25 to 30 service failures had been reported, and there had been over 200 instances of SCC occurring during hydrostatic retests or detected by visual observation. Characteristically, the SCC was observed on gas transmission line pipes with apparently normal properties corresponding to yield strengths in the range 288 to 496 MPa (41.8 to 72 ksi), most commonly after about 25 years of underground service.

The SCC originates on the soil side of pipes which are most commonly coated and under cathodic protection and are at a temperature somewhat above ambient. According to Wenk, temperatures at the time of failure have ranged from 13 to 57°C (55 to 135°F), and have usually been above 35°C (95°F). SCC failures have occurred at hoop stresses ranging from 160 to 270 MPa (23.2 to 39.3 ksi), equivalent to 46 to 76% of the specified minimum yield strength of the pipes involved.

The condition of the pipe coating has been observed to be important, with the SCC often occurring under a disbonded region of the coating which may contain a pocket of solution deriving from the ground water. Analysis of the solutions found

*SCC is used in this report as denoting an active path corrosion (APC) mechanism.

under disbonded coatings near failure sites showed alkaine pH values (9.6 to 12.3) and substantial quantities (0.4 to 1.4%) of both carbonate and bicarbonate ions.

Examinations of the surfaces of failed pipes show that the SCC usually occurs in clusters of parallel cracks oriented along the length of the pipe, i.e., normal to the direction of the hoop stress. No association of the cracks with the mill welds is indicated. Examination of the crack faces shows a dark corrosion product near the origin and a crack path that is generally intergranular, with a tendency towards branching.

Extensive laboratory investigations have been reported [3,4] on the SCC behaviour of line-pipe steels in three model solutions representing three possible SCC mechanisms (nitrate, hydroxide and carbonate-bicarbonate). Some of the characteristics of SCC, as indicated by the results of these studies, are summarized in Table 1. In terms of these findings, the researchers consider that they have achieved a good general understanding of the SCC mechanism in line pipes, though many details remain to be elucidated. In brief, it is thought that the cathodic protection currents drive moisture through micropores and holidays in the protective coating to the pipe wall. The cathodic current causes an alkaline pH to develop at the pipe wall. Ingress of CO_2 from the surroundings may bring about the formation of carbonates and bicarbonates. These processes may be accompanied by disbonding of the coating such that a small pocket of carbonate-bicarbonate solution (for example) is produced at the pipe wall which is partly shielded from cathodic currents. The electrochemical potential at the pipe wall within the disbonded area can then exhibit a value less negative than that applied for cathodic protection, lying within the range required for carbonate-bicarbonate cracking. Normal operation of the pipeline provides the required sustained tensile stress (augmented by various types of stress raisers, residual stresses, etc.). Slow fluctuations in pressure which occur during operations are thought to strain the metal (for at least a fraction of the time) at rates lying

within the range needed for SCC to occur.

Fessler [5] has considered practical approaches to the solution of the SCC problem. For pipe already in the ground, the control of pressure fluctuations and the lowering of compressor discharge temperatures are considered to be most feasible. For pipelines installed in the near future, the use of new inhibitor-containing coatings, complete removal of mill scale before coating, and more care in coating application, inspection and maintenance, are proposed. On a longer-term basis, a number of other approaches, including changes to the steel composition and its heat treatment condition, might warrant consideration.

To the present, service failures by SCC of natural gas or crude-oil transmission pipelines are not known to have occurred in Canada. However, the nature of the phenomenon (in particular the long induction period which is typical), suggests that this problem is likely to manifest itself sooner or later. The complexity and unpredictability of the SCC problem in transmission pipelines, and its potential economic significance, indicate that research at PMRL is warranted.

It was decided to perform exploratory SCC tests on specimens of line-pipe steel immersed in the three laboratory solutions used by other workers [3,4]. A simple, inexpensive technique was selected; namely, the use of small bent-strip specimens and procedures resembling those developed by Uhlig and Sava [6] and used previously at PMRL [7]. As a modification to the earlier approach, and to fulfill one of the requirements for SCC, it was decided to strain the specimens while they were immersed in the test solutions. As a primary objective, it was decided to attempt to determine the minimum temperature for SCC in each of the three solutions.

EXPERIMENTAL

1. Specimens

The strip test specimens used in this work were obtained from the parent metal of line-pipe F, described in Table 2. Specimens dimensions were 44.5 x 6.4 x 1.0 mm (1.75 x 0.25 x 0.040 in.) and the specimens were fabricated so that the specimen length was transverse to the line-pipe length and the specimen thickness direction corresponded to that of the line pipe. Machined surfaces were described as "12 micro-inch centre line average". Prior to testing, two 0.70 mm (0.027 in.) diam holes were drilled through the specimen on a line equidistant from the two ends of the specimen. Spacing between the two hole centres was 3.18 mm (0.125 in.) and each centre was equidistant from the edge of the specimen. The use of drilled holes as a means of concentrating stresses resembled the practice of researchers at Shell Development Co. [8], and the hole sizes and placement used in this work were identical to those employed by Ogle [9]. In a few cases, specimens were not provided with stress raisers and are designated "smooth".

2. Pre-bending of specimens

Prior to tests, specimens were bent to a standard chord length of 36.5 mm (1.44 in.). The bending was done in two stages. First, the as-machined specimen was partially bent in four-point loading, using a specially constructed device. Without allowing spring-back, the specimens were then placed between the ceramic inserts in the jaws of the Inconel rig (Fig. 1). Following a degreasing, the loading screw at the upper part of the rig was used to move the upper sliding arm, bending the specimen to the standard chord length for immersion in the test solution.

When it was necessary to attach an electrical conductor to the specimen, this was always done prior to the pre-bending, by spark-welding a fine wire of iron or mild steel to the lower half of the specimen.

Bending a smooth specimen to the standard chord length imparted a permanent deformation, with an elongation of about 10% in the steel used [9]. During tests, specimens were held in their bent configuration by a compressed spring at the upper end of the sliding arm. A force of about 135N (30 lb) was required for full compression, and this provided a following load for both creep and crack propagation. Subsequent to SCC of specimens, a sufficient movement of the sliding upper arm of the rig opened a micro-switch, deactivating a timer.

3. Straining of specimens during tests

In all tests, specimens were immersed initially at the standard chord length either until SCC was shown by the timer, or for some pre-selected period. In most cases, specimens which had not failed by SCC were then strained additionally, without removal from the solution, by tightening the loading screw at the upper end of the Inconel rig. The tightening was performed in increments, following a pre-selected schedule. Usually each increment consisted of one full turn, and turns were made once/hr, 3 times/day or once/day. For convenience, when 3 turns were made in one day, they were performed at 4-hr intervals during the working day, e.g., at 8:00 a.m., 12 noon and 4:00 p.m. Each full turn of the loading screw would be expected to alter the chord length of the bent strip by 1.27 mm (0.050 in.), though deviations would be expected because of different amounts of compression of the spring.

Figure 2 shows the results of an Instron test in air on specimens of steel F which had been bent only slightly at the beginning of the test, after which the chord length had been decreased continuously at a constant rate. The load was monitored

continuously and it can be seen that it decreases steadily as the chord length decreases to about 20 mm (0.8 in.). After this, there is a slight increase in load, related to slippage of the specimens on the ceramic end pieces. Based on these findings, the maximum number of turns of the loading screw during tests was fixed at 12, yielding an approximate minimum specimen chord length of 22.3 mm (0.84 in.).

4. Test solutions and apparatus

The following test solutions were used [3,4]. A typical pH value is shown for each:

20% $NH_4NO_3^*$ (pH 6.2)

33% NaOH** (pH ~ 14)

1 N Na_2CO_3 - 1 N $NaHCO_3$ (pH 9.3)

The tests in 20% NH_4NO_3 were all performed under free-corrosion conditions. A single specimen was immersed in one litre of freshly prepared solution contained under reflux in a pyrex flask controlled at the desired temperature. For the other two test solutions, a few free-corrosion tests were performed as above, but most of the tests were at controlled potentials and involved immersion of a single specimen in 2 1/2 or 3 litres of unstirred test solution. The solution was in contact with air and contained in a 4-litre beaker. Most of the tests were performed in freshly prepared solutions. In the case of the 1 N Na_2CO_3-1 N $NaHCO_3$ solution, 2 or 3 short tests were sometimes performed in the same batch of solution. Solutions were monitored for thermal degradation of bicarbonate to non-cracking carbonate [10] by measurements of pH. (Na_2CO_3 solutions have a pH of about 12, whereas $NaHCO_3$ solutions have a pH of about 8.5).

The 4-litre beakers used in the tests were provided with a plastic or glass lid with holes drilled through it. This permitted the use of conventional methods to obtain reflux and potentiostatically control specimen potential through the use of a fine (coated) steel wire spark-welded to the lower end of the

*About 2.7 N NH_4NO_3 **About 11.2 N NaOH

specimen, a platinum auxiliary electrode, and salt bridges leading to a SCE electrode. For all tests in 33% NaOH, a stainless steel beaker was used and the solution was contacted by rubber tubing instead of glass. Temperatures were controlled using conventional methods, with the flasks or beakers immersed in bath oil or a bed of fine sand, or standing on a hot plate. In some experiments, a lower than ambient temperature was obtained by standing the stainless steel beaker on an electrically operated cooler plate.

RESULTS

1. Free-corrosion potentials

In each of the three solutions used the free-corrosion (f.c.) potential of steel F was determined over a range of temperatures. This was done by first immersing an unstressed, degreased specimen in one litre of the selected solution at room temperature. After recording the SCE potential, additional potential measurements were then made as the temperature of the solution was increased to the boiling point during a period of about 2 hr. The results obtained are shown in Figs. 3 to 5, which also provide the room-temperature pH of each solution. For the results in 20% NH_4NO_3, the data points from three runs are combined, whereas each of the other solutions was investigated by a single run.

2. SCC tests in 20% NH_4NO_3

Specimens were bent to the standard chord length and immersed in the test solution at temperatures from 30 to 101.5°C (86 to 215°F). They were then allowed to corrode freely (weight losses of 3 to 5 $mg/cm^2/hr$) until an SCC failure occurred, or until some pre-selected period of time had elapsed.

Some of the "constant deflection" specimens failed spontaneously, as indicated by the timer, after immersion periods

less than 20 hr (Table 3). Examinations of specimen surfaces showed a few parallel, deeply penetrating cracks at or near the stress raisers, transverse with respect to the specimen length. Metallographic sections showed that the SCC was almost completely intergranular (Fig. 6). Constant deflection specimens which did not fail by SCC spontaneously were left in the test solution for periods as long as one week. Without examining the surfaces to determine whether SCC had occurred, they were then strained additionally in the solution as indicated in Table 3. At the end of the test, specimen surfaces were examined for SCC, using a low-power stereomicroscope. In a few cases, this was supplemented by preparing sections of the specimens and examining them at high magnification. As shown in Table 3, four of the six specimens which had been strained in the test solution showed SCC. Exceptions were a specimen tested at 30°C (86°F) and a specimen tested at 40°C (104°F) which had been given a prior immersion at constant deflection of only 1.1 hr.

A few smooth specimens were tested under constant deflection conditions. The results, shown in Table 3, suggest similar behaviour to the specimens with stress raisers. Straining of the specimens in the solution was not attempted.

In these tests, f.c. potentials were not determined. Results obtained at 50°C (122°F) on an unstressed specimen of steel F appear in Fig. 7.

3. SCC tests in 33% NaOH

With the exception of three f.c. tests at 101.5°C (215°F), the measurements were performed at a potentiostatically controlled potential of -0.96 V, at temperatures varying from 50 to 95°C (122 to 203°F), (Table 4).

After immersions at constant deflection ranging from 24 to 158.9 hr, no indication of SCC, in terms of timer arrest, was shown by any specimen. Specimens were therefore given subsequent straining in the solution, using the schedules given in Table 4. After completion of tests, the surfaces of the specimens were examined. In the specimens in which SCC was observed, it appeared in the form of a number of parallel cracks oriented transverse to the specimen length, in the area near the stress raisers which shows strain lines on bending in air.

Sections of specimen 30 showed numerous shallow intergranular microcracks on the specimen surface. There were also some broader, shallow cracks with intergranular microcracks originating from them (Fig. 8). There were also surface features which had the appearance of corrosion pits, or cracks which had been opened up by straining in solution. Some of these had not served as sites for additional SCC, as shown in Fig. 9. Highly strained metal is to be seen at "bridges".

4. SCC tests in 1 N Na_2CO_3 - 1 N $NaHCO_3$

With the exception of two f.c. tests performed at 101.5°C (215°F), specimens were potentiostatically controlled at potentials in the range -0.55 to -0.67 V, at temperatures in the range of 6 to 96°C (43 to 205°F), (Table 5). The results of Sutcliffe et al [10] were used to select, as much as possible, potentials for maximum susceptibility to SCC at each temperature.

As in the tests in 33% NaOH solution, specimens immersed at the standard chord length, for up to one week, did not exhibit SCC. All specimens were, therefore, strained in the solution following the initial immersion, using the schedules given in Table 5. As indicated in this table, specimens were sometimes removed from the test solution after the original constant deflection immersion or at intermediate stages of the schedule. Without removing the specimen from the Inconel rig, surfaces were

rapidly cleaned and dried, then examined for SCC, using a low-magnification stereomicroscope. If SCC had not occurred, the specimens were re-immersed. As observed in the tests in 33% NaOH solution, SCC showed up in the vicinity of the stress raisers as a number of parallel cracks and shallow fissures, lying transverse to the specimen length. A particularly distinct example is reproduced in Fig. 10.

Sections through the cracks showed shallow, intergranular penetrations, resembling the SCC observed in specimens exposed to 33% NaOH. At their origins, cracks were usually broad, with finer intergranular branching microcracks extending further into the metal (Fig. 11).

During the short exposure to f.c. conditions just before potentiostatting, a machined specimen of steel F usually showed a potential consistent with the values given in Fig. 5, i.e., -0.3 to -0.4 V. However, on occasion, f.c. values of -0.85 to -0.95 V were seen. After polarization into the potential range causing cracking, subsequent f.c. values were invariably in the vicinity of -0.9 V.

Polarization tests were performed on specimens of steel F which had been surface-ground on 600-grit paper. The expected active-passive behaviour was exhibited in the polarization curves, Fig. 12 being a typical example. It is seen that it is possible for corrosion to occur at a value near -0.9 V, with reduction of hydrogen ions providing the cathodic mechanism. Alternatively, corrosion can take place in the passive region, at more noble potentials, the cathodic mechanism presumably being the reduction of dissolved oxygen.

DISCUSSIONS OF RESULTS

1. SCC tests in 20% NH_4NO_3

The results of Table 3 showed that freely corroding steel F was highly susceptible to SCC over the temperature range 30 to 101.5°C (86 to 215°F). Other workers [6,11] have used the time-to-failure parameter successfully in studies of the SCC of iron and mild steel in nitrate solutions. However, in the present work, reproducibility was poor. This is probably related to initial attempts to obtain a "hair-trigger" response of the micro-switch to specimen movement, by fine adjustment of the contacting screw. Before the series of tests in NH_4NO_3 had been completed, it was realized that this could not be done reproducibly. Thereafter (and for all specimens in the other two solutions), the contacting screw was adjusted initially for full closure of the micro-switch button. This signified that an appreciable movement of the sliding upper arm of the rig was needed to cause timer arrest. Because the nitrate medium was not considered of primary importance to SCC of line-pipe steels, it was not deemed worthwhile to repeat the tests in an effort to improve reproducibility. Rather, the results were taken as a go/no-go index of susceptibility to nitrate SCC under the various conditions investigated.

Straining of the specimens in the test solution was performed primarily to bring about a positive result for specimens which had not failed in a standard chord length exposure. Table 3 shows that additional straining was usually needed at the lower test temperatures, where SCC susceptibility would be expected to be diminished. At 40°C (104°F), the effect of immersion time prior to straining was investigated. It was found that 1.1 hr at standard chord length was insufficient, whereas 40.5 hr produced SCC. However, the SCC in the latter case was not as clearly defined as that observed after a prior immersion of 162.7 hr. Consideration of Fig. 7 suggests that at the lower

temperatures, it might require 1 or 2 days for a steady state potential to be attained. It is possible that only after that can SCC occur. Along the same lines Flis [11] has reported that rapid SCC of iron in 5 N NH_4NO_3 solutions is connected with the formation of a passivating film of γ-Fe_2O_3. Such films were found to form readily at higher temperatures, but are produced more slowly as temperature is decreased. At room temperature, Fe_3O_4 is reportedly produced, and the SCC propagation rate is lowered by a factor of about 1000.

A few tests performed with smooth specimens showed SCC behaviour resembling that of specimens with stress raisers. In highly corrosive 20% NH_4NO_3, it appears that this type of specimen can be used.

2. SCC tests in 33% NaOH

In contrast to its behaviour in 20% NH_4NO_3, steel F was relatively resistant to SCC in 33% NaOH (Table 4). In no case did constant deflection specimens fail spontaneously by SCC in terms of a timer arrest. Rather, it was necessary to strain the specimens in the solution, then examine surfaces for SCC. Timer arrests never occurred during the straining programs. Of 9 specimens tested at -0.96 V, only 4 were susceptible, the minimum temperature for SCC being 60°C (140°F).

Various straining schedules were followed. It was found that daily increments of strain were more effective than hourly increments in bringing about SCC. There were indications that three increments of strain per day might be even more effective.

Smooth specimen 41S did not show SCC using a straining schedule which would have been expected to produce SCC in specimens with stress raisers. It appears, therefore, that the stress raisers promote SCC in 33% NaOH.

Berry [4] was able to detect SCC in specimens from X-52 line-pipe in 33% NaOH at a minimum temperature of 38°C (100°F), using very slow constant strain rates. Non-propagating cracks were observed at even lower temperatures, down to 22°C (72°F). Assuming that steel F is as susceptible to SCC as X-52, this indicates that the constant strain method is more sensitive to SCC than that employed in the present investigation. However, it should be noted that straining schedules other than those attempted might have lowered the threshold temperature for SCC. The use of a sharper notch in the specimen might have had a similar effect. These and other factors were not investigated at this time because of statements that carbonate-bicarbonate solutions were more relevant to the SCC problem [12].

3. SCC tests in $\underline{N}$ Na_2CO_3-$\underline{N}$ $NaHCO_3$

At the higher test temperatures, SCC behaviour in $\underline{N}$ Na_2CO_3-$\underline{N}$ $NaHCO_3$ resembled that in 33% NaOH. However, as the temperature was progressively lowered, behaviour in the two solutions diverged, with the carbonate-bicarbonate causing SCC down to a minimum temperature of 22°C (72°F). As in the caustic solutions, specimens immersed at standard chord length never showed SCC. Only after a subsequent straining in the solution was SCC observed. On only one occasion did a timer arrest occur during a straining schedule.

Various straining schedules were used, with prior immersion at constant deflection either overnight or over the weekend. At the lower temperatures, 3 turns of the loading screw per day, to a total of 6 to 12 turns, appeared to be an effective means of causing SCC. At the higher temperature, 1 turn per hr (to a maximum of 6) was sufficient for SCC. For both loading schedules there were indications that longer prior immersions at constant deflection promote SCC.

Smooth specimens were tested at 70°C (158°F). Though they were apparently less susceptible than similar specimens with stress raisers, SCC was produced.

In agreement with the findings of the present study, Berry [4] demonstrated SCC in a carbonate-bicarbonate solution at 21°C (70°F). Similarly, Sutcliffe et al [10] observed intergranular SCC at temperatures as low as 22°C (72°F). In so far as SCC in carbonate-bicarbonate solutions is concerned, the methods used in the present study appear to be acceptably sensitive.

4. Experimental methods

The specimen type and stressing methods used in this research had the advantages of being simple and inexpensive. With little further modification, the methods employed in this study might be used in the comparison of different line-pipe steels, environments, and SCC-inhibitors.

However, a number of improvements to the apparatus are under consideration. The manual performance of straining schedules can be highly inconvenient. It is, therefore, planned to attach a geared-down electrical motor to the loading screw so that the latter can be driven continuously at pre-selected slow rates. By suitable arrangements, the timer can be made to respond to the attainment of some pre-selected low chord length, indicative of definite failure of the specimen (e.g., about 20 mm or 0.8 in.) The time to failure would then be expected to reflect the amount of SCC occurring during the straining operation. Other possibilities include the use of sharper stress raisers or smooth specimens, and continuous monitoring of specimens during tests by strain gauges.

SUMMARY AND CONCLUSIONS

1. SCC tests have been performed on small bent strips of a controlled-rolled line-pipe steel with a yield strength of 448 MPa (65 ksi). The test solutions had been developed elsewhere to study line pipe SCC in the laboratory (20% NH_4NO_3, 33% NaOH, $\underline{N}$ Na_2CO_3-$\underline{N}$ $NaHCO_3$).

2. In 20% NH_4NO_3, SCC was observed for freely-corroding specimens at temperatures from 30 to 101.5°C (86 to 215°F).

3. In 33% NaOH, SCC occurred for specimens at a potential -0.96 V (SCE), which had been strained in the solution. The minimum temperature for SCC was 60°C (140°F).

4. In $\underline{N}$ Na_2CO_3-$\underline{N}$ $NaHCO_3$, potentials were altered according to temperature, in the range -0.55 to -0.67 V SCE. For specimens which had been strained in the solution, the minimum temperature for SCC was 22°C (72°F).

5. It is concluded that the experimental methods employed could be useful in comparisons of different line-pipe steels, environments, and SCC inhibitors, but that modifications of the apparatus are needed.

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Table 1 - Laboratory observations on SCC of line-pipe steels (3,4)

	Test Solution		
	1N Na_2CO_3-1N $NaHCO_3$	33% or 35% NaOH	20% NH_4NO_3
Temperature Range	21°C (70°F) to boiling	38°C(100°F)to boiling (Non-propagating cracks at 22°C (72°F)	24°C(75°F) to boiling
Stress Required	Above YS	Above YS	Below and above YS
Potential Range	-0.60 to-0.70V (SCE) -0.67 to-0.77V(Cu/$CuSO_4$)	-0.88 to -1.05V (SCE) -0.95 to -1.12V (Cu/$CuSO_4$)	+1.27 to -0.33V (SCE) +1.20 to -0.40V(Cu/$CuSO_4$)
Straining Rate Range	10^{-7} to 10^{-5} sec^{-1}	$<10^{-7}$ to 4 x 10^{-6} sec^{-1}	Constant straining not needed
SCC Propagation Rate: at 25°C (77°F)	1 to 2 x 10^{-7} mm sec^{-1} (0.3 to 0.7 mils/day)	-	6x10^{-5} to 2x10^{-3} mm sec^{-1} (200 to 7000 mils/day) (temperature not given)
at 60°C (140°F)	9 x 10^{-7} mm sec^{-1} (3 mils/day)	10^{-6} mm sec^{-1} (3.3 mils/day)	
at 90°C (194°F)	3 x 10^{-6} mm sec^{-1} (11 mils/day)	3.5 x 10^{-6} mm sec^{-1} (12 mils/day)	

Table 2 - Description of line-pipe steel F

Pipe Size:	915 x 13.2 mm (36 x 0.518 in.) (OD x wall thickness)	
API 5LX X-65:	controlled-rolled, longitudinally welded.	
Yield Strength:	463 MPa (67.2 ksi)	
UTS:	633 MPa (91.8 ksi)	
Elongation (in 50 mm):	32%	
Charpy Test:	2/3 Charpy, 57J (42 ft lb) 97% shear @ -4°C (25°F)	
Composition, %	C	0.16
	Mn	1.25
	P	0.008
	S	0.009
	Nb	0.047
	Si	0.35

Table 3 - SCC behaviour of steel P in 20% NH_4NO_3 solution

Specimen No.	Temp. °C	Temp. °F	Potential, Volts(SCE)	Period at Constant Deflection, hr	Straining Schedule: Turns of Loading Screw per Increment	Straining Schedule: Increment Rate	Straining Schedule: Total Turns of Loading Screw	Behaviour
10	101.5	215	f.c.	0.13	0	0	0	SCC
11	"	"	"	9.1	0	0	0	SCC
12	"	"	"	18.1	0	0	0	SCC
14	85	185	"	0.20	0	0	0	SCC
15	"	"	"	169 NF	1	1/hr	7	SCC
24S	75	167	"	24 NF	0	0	0	SCC(MS)
25S	"	"	"	6.5	0	0	0	SCC
16	70	158	"	0.15	0	0	0	SCC
17	55	131	"	6.9	0	0	0	SCC
26S	50	122	"	144 NF	0	0	0	No SCC
18	40	104	"	162.7 NF	1	1/hr	7	SCC
20	"	"	"	40.5 NF	1	1/hr	7	SCC
19	"	"	"	1.1 NF	1	1/hr	7	No SCC
22	30	86	"	166.6 NF	1	1/hr	7	SCC(MS)
23	"	"	"	168.1 NF	1	1/hr	7	No SCC(MS)
21	"	"	"	0.35	0	0	0	SCC

S = smooth specimen
NF = no timer indication of SCC
MS - Metallographic section prepared to check for SCC

Table 4 - SCC behaviour of steel F in 33% NaOH solution

Specimen No.	Temp. °C	Temp. °F	Potential, Volts (SCE)	Period at Constant Deflection, hr	Straining Schedule: Turns of Loading Screw per Increment	Straining Schedule: Increment Rate	Straining Schedule: Total Turns of Loading Screw	Behaviour
6	101.5	215	f.c.	158.9 NF	0.5	1/hr	4	No SCC
				16.0 NF	0.5	"	3.5	No SCC
9	"	"	"	14.8 NF	0.5	"	5	No SCC
13	"	"	"	41.5 NF	1	"	5	No SCC
30	95	203	-0.96	24 NF	1	1/day	3	SCC
35	"	"	"	16 NF	1	1/hr	6	SCC
418	"	"	"	17.4 NF	1	1/hr	5	No SCC
33	72	162	"	98 NF	1	1/day	4	SCC
29	"	"	"	24 NF	1	1/day	1	No SCC
36	"	"	"	18 NF	1	1/hr	6	No SCC
61	60	140	"	70.8 NF	1	3/day	9	SCC
62	"	"	"	64.2 NF	1	1/day	4	No SCC
34	50	122	"	72 NF	1	1/day	4	No SCC
60	"	"	"	69.8 NF	1	3/day	7½	No SCC

S = smooth specimen
NF = no timer indication of SCC

Table 5 - SCC behaviour of steel F in 1M Na_2CO_3-1M Na HCO_3 solution

Specimen No.	Temp. °C	Temp. °F	Potential, Volts (SCE)	Period at Constant Deflection, hr	Straining Schedule: Turns of Loading Screw per Increment	Straining Schedule: Increment Rate	Straining Schedule: Total Turns of Loading Screw	Behaviour
5	101.5	215	f.c.	160.1 NF	0.5	1/hr	3.5	No SCC (MS)
7	"	"	"	16.9 NF	0.5	1/hr	4	+
				17.0 NF	0.5	1/hr	3.5	No SCC (MS)
40	96	205	-0.63	16.4 NF	1	1/hr	6	SCC (MS)
42	90	194	-0.63	17.5 NF	1	1/hr	6	SCC (MS)
45	"	"	-0.67	17.7 NF	1	1/hr	6	SCC
46	"	"	-0.67	163.3 NF*	1	1/hr	6	SCC
50	"	"	-0.67	1 NF	1	1/hr	6	No SCC*
					1	"	2	+
				15 NF	0	0	0	SCC
51	70	158	-0.64	16.2 NF	1	1/hr	6	SCC
52	"	"	-0.64	65.5 NF	1	3/day	6	SCC
63S	"	"	-0.64	17.8 NF	1	1/hr	6	No SCC*
						"	12	SCC
64S	"	"	-0.64	66 NF	1	3/day	6	No SCC*
					1	"	9	No SCC*
						"	12	No SCC
53	50	122	-0.60	66.6 NF	1	3/day	2	SCC shown by timer after 71.1 hr.
56	"	"	-0.60	18.0 NF	1	3/day	3	No SCC*
					1	"	6	SCC
65	"	"	-0.60	17.7 NF	1	1/hr	6	No SCC*
						"	12	SCC
57	35	95	-0.57	68.5 NF	1	3/day	3	No SCC*
					1	"	6	No SCC*
					1	"	9	SCC
58	22	72	-0.55	68.3 NF	1	3/day	3	No SCC*
					1	"	6	No SCC*
					1	"	9	SCC
59	6(1)	43	-0.55	70.7 NF	1	3/day	9	No SCC

S = smooth specimen
NF = No timer indication of SCC
MS = Metallographic section prepared to check for SCC

(1) Some of the solutes precipitated out.
* = Examination using stereomicroscope indicated no SCC. Specimen re-immersed.
+ = Without examining specimen, test continued as shown next line

Fig. 1. Inconel rig used in the SCC tests showing a bent specimen.

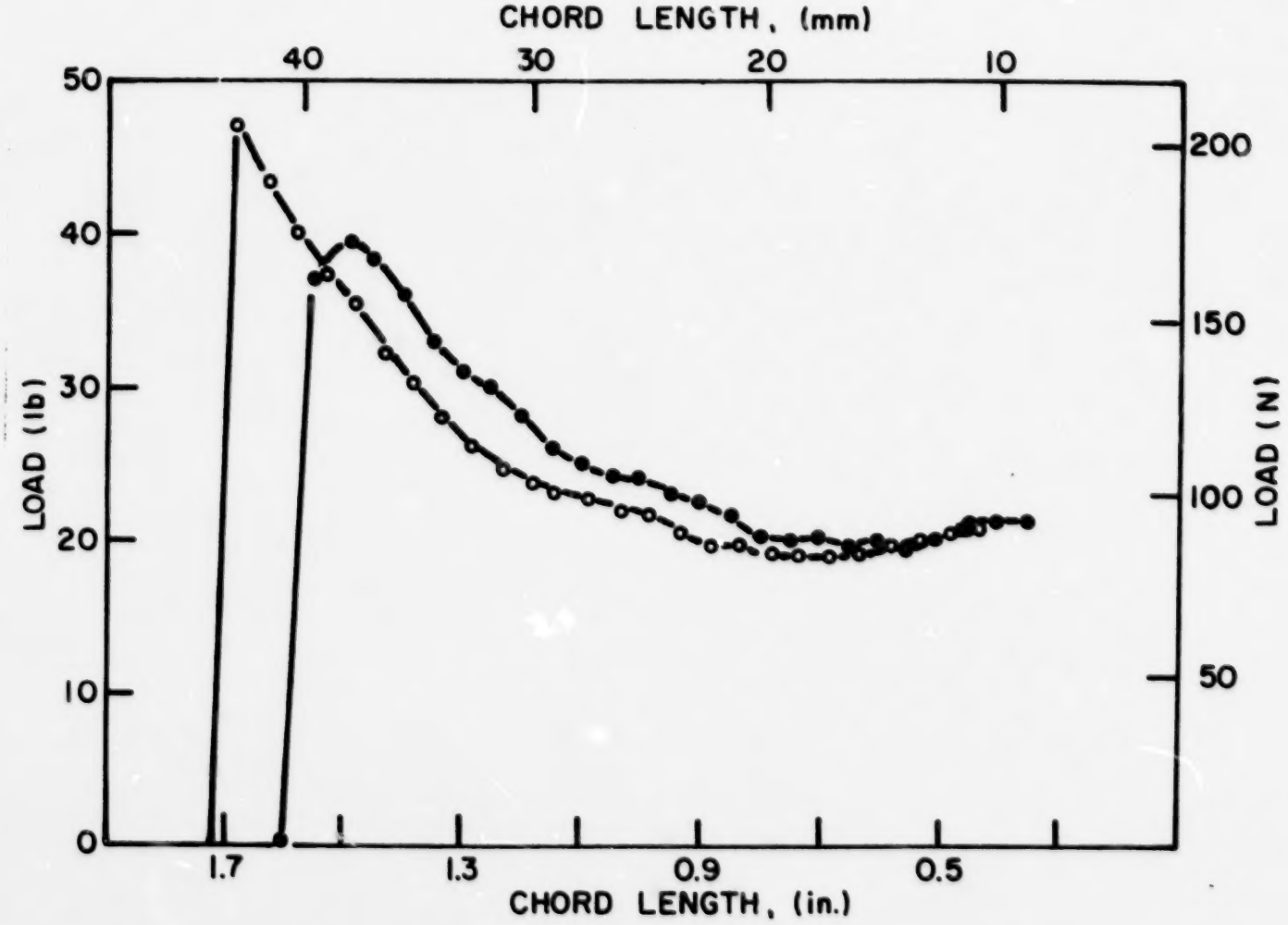


Fig. 2. Load vs. chord length for two specimens of steel F (Instron head speed: 1.27 mm (0.05 in.) per min).

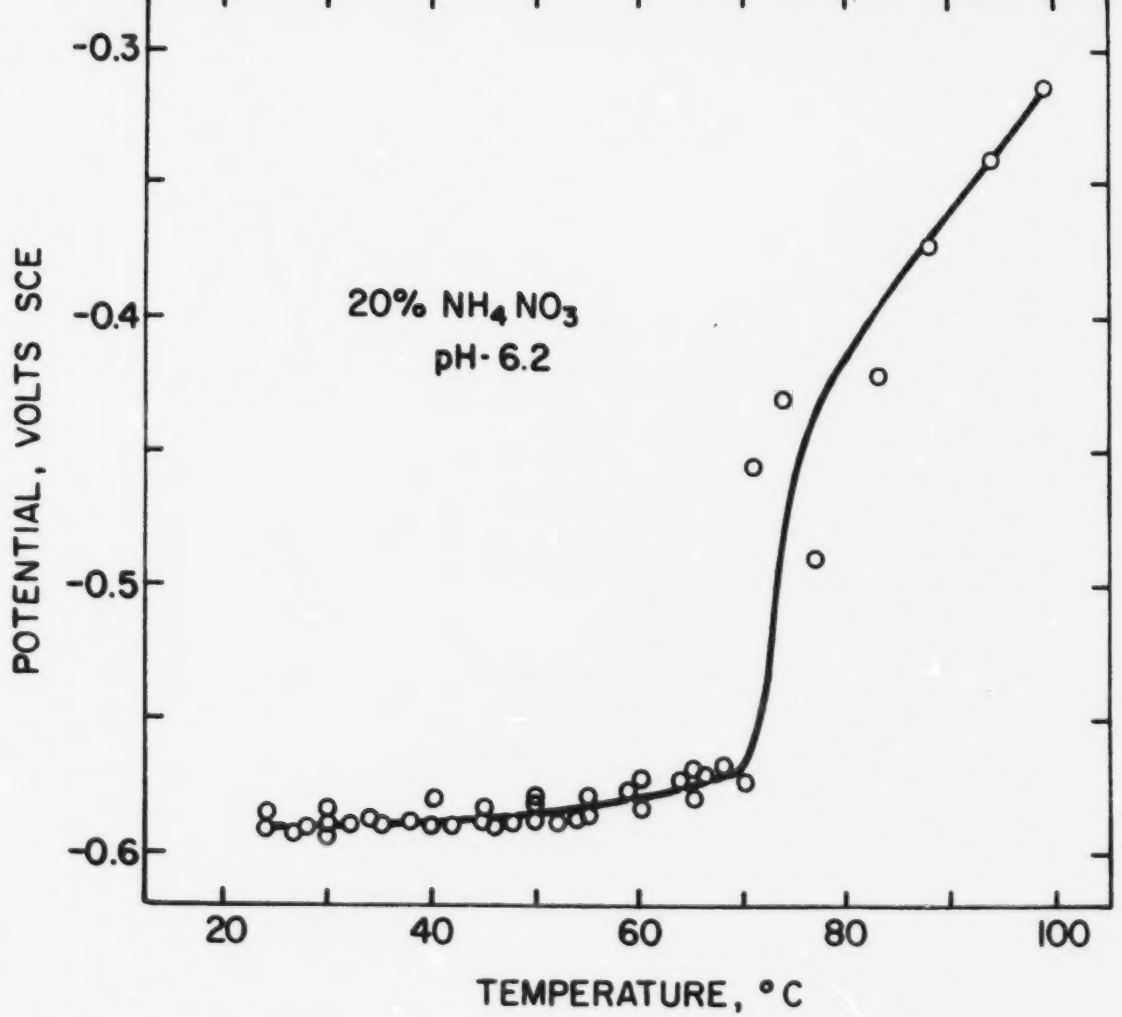


Fig. 3. Effect of temperature upon potential of steel F in 20% NH_4NO_3 solution.

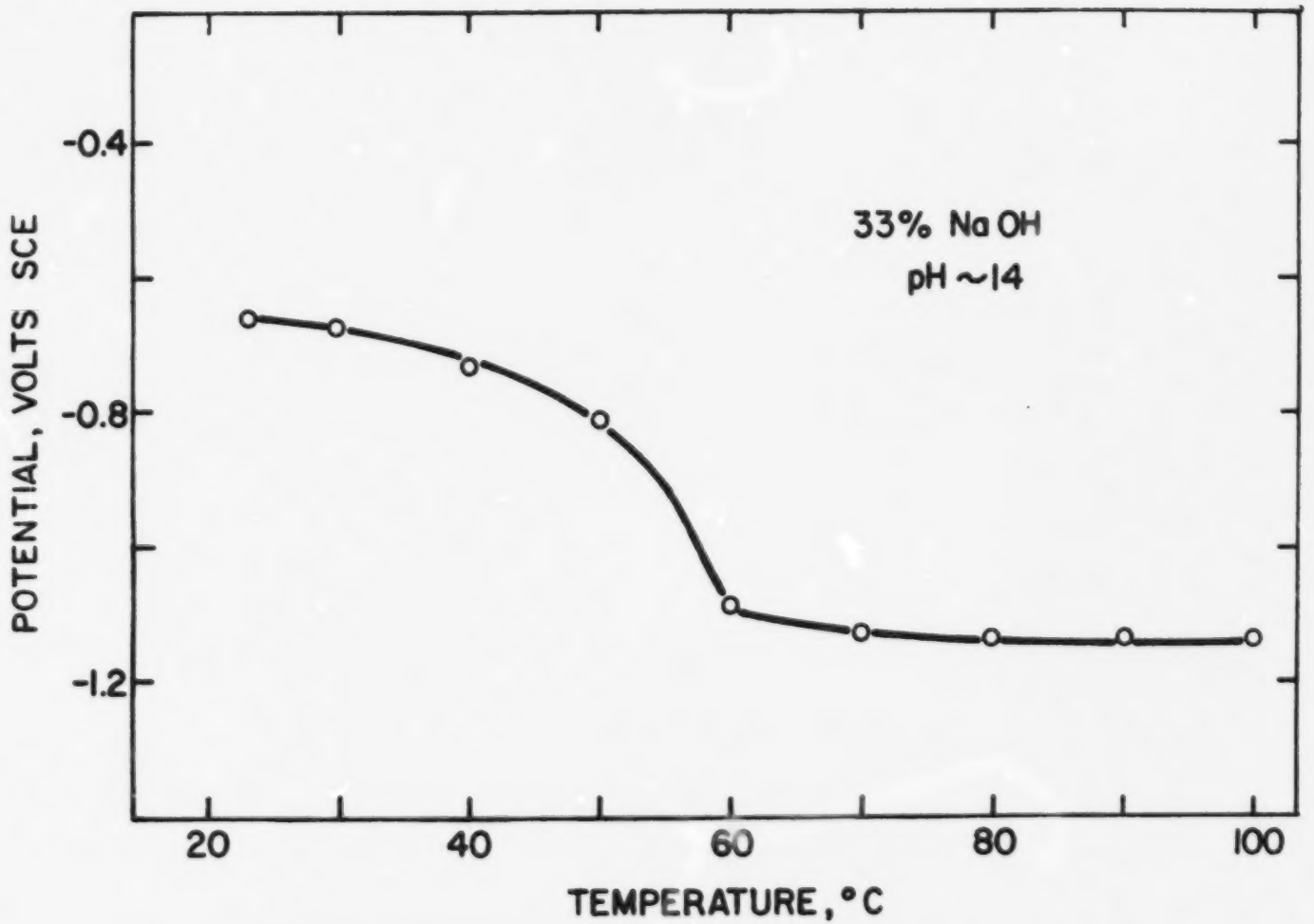


Fig. 4. Effect of temperature upon potential of steel F in 33% NaOH solution.

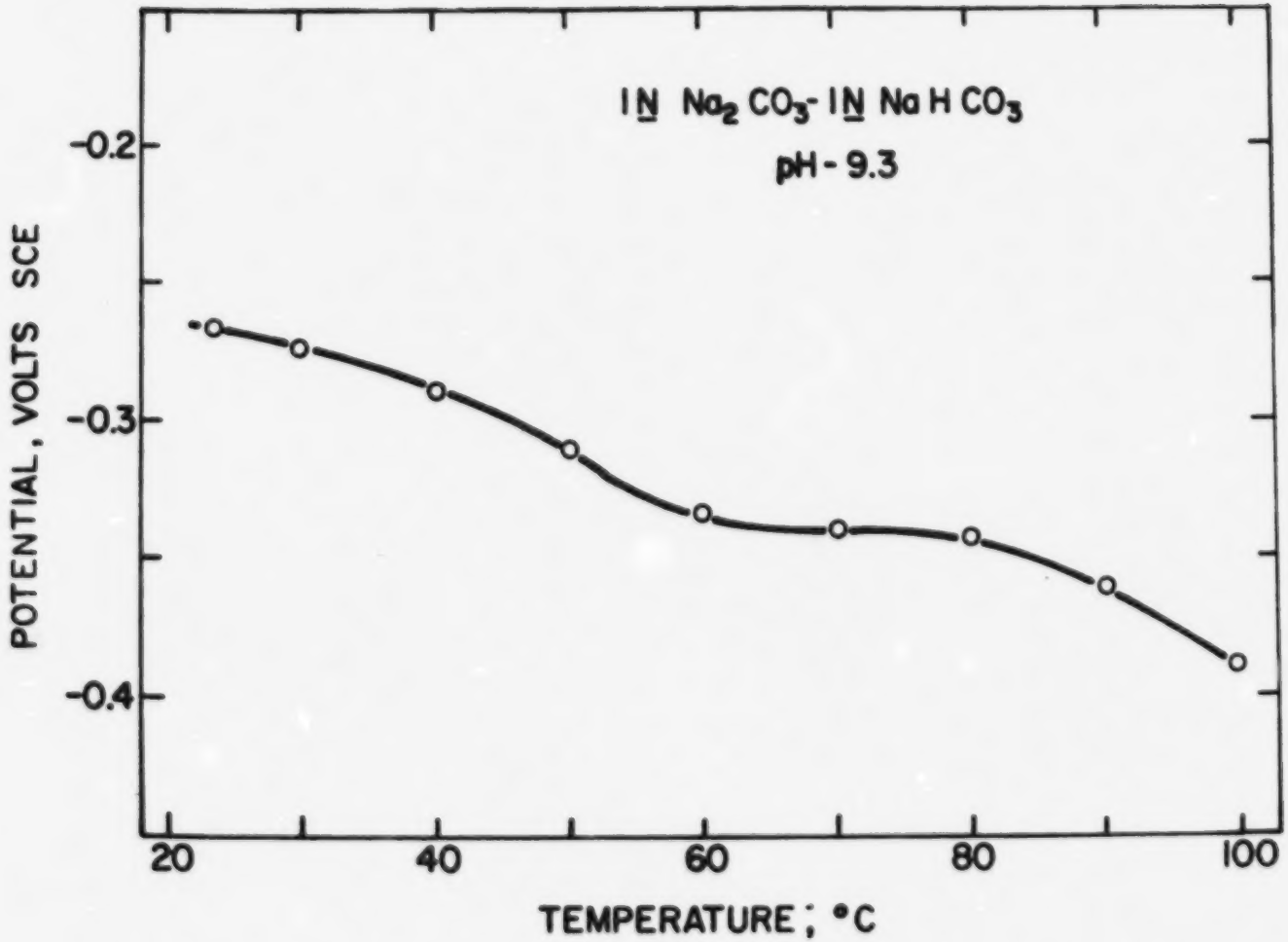


Fig. 5. Effect of Temperature upon the potential of steel F in1 N Na_2CO_3-1 N $NaHCO_3$ solution.

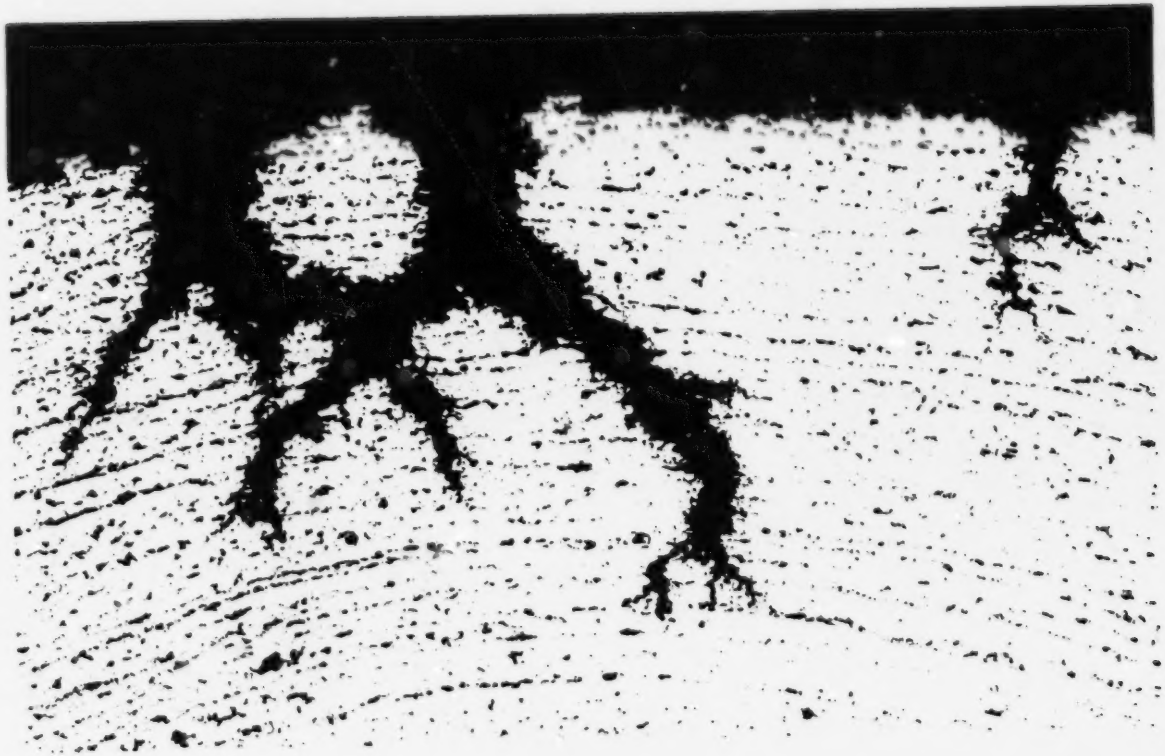


Fig. 6. Intergranular SCC in specimen 12, tested at 101.5°C (215°F) in 20% NH_4NO_3. X150

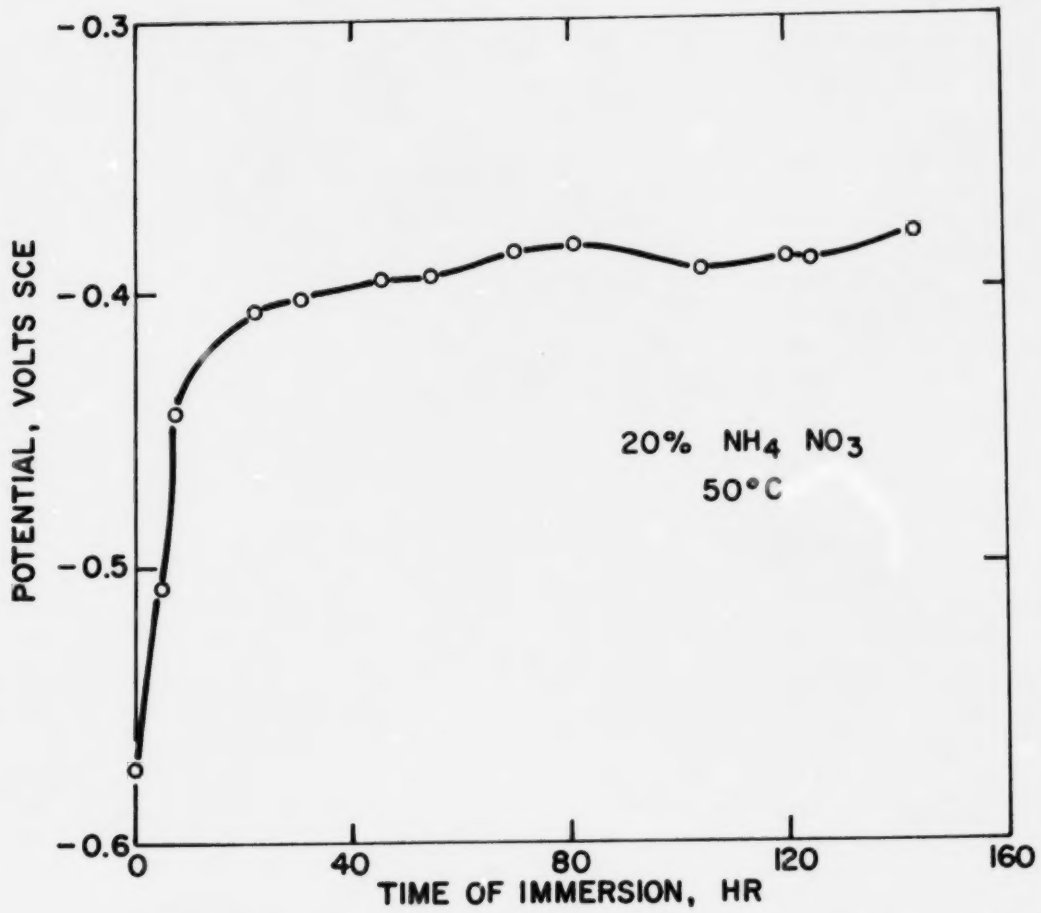
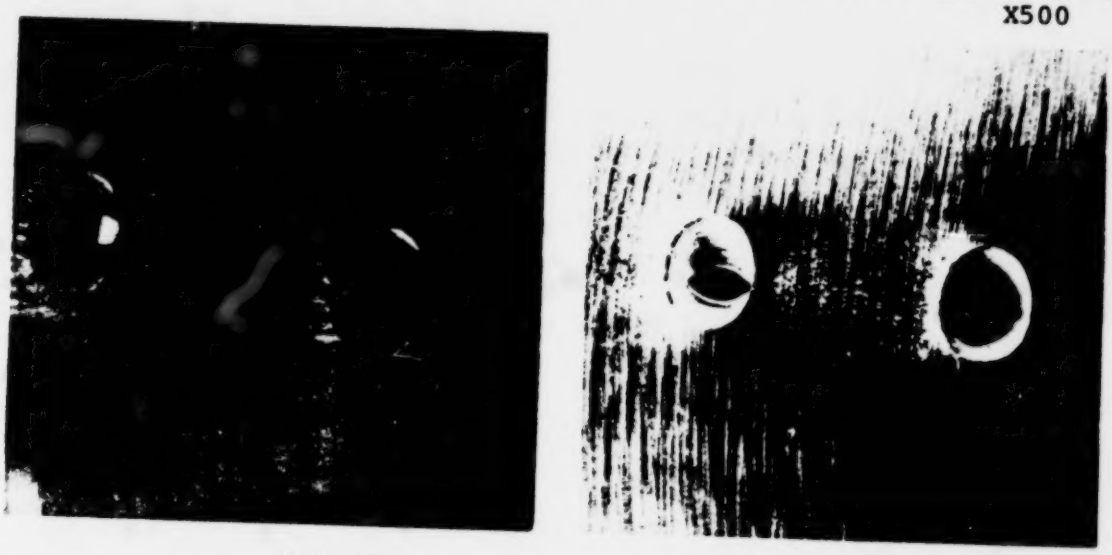


Fig. 7. Free-corrosion potential vs. time of immersion of steel F in 20% NH_4NO_3 solution at 50°C (122°F).

Fig. 8. Section showing intergranular SCC in specimen 30, tested in 33% NaOH at 95°C (203°F) and -0.96V (SCE). X880

Fig. 9. Section showing corrosion pit or strained crack in specimen 30, tested in 33% NaOH at 95°C (203°F) and -0.96 V (SCE). X500



(a) X14.7 (b) X13.7

Fig. 10. Scanning electron microscope photographs of two specimens of steel F. The lengths of the specimens are normal to the centre line of the holes.

(a) Specimen 52, tested in 1 N Na_2CO_3 - 1 N $NaHCO_3$ at 70°C (158°F) and -0.64 V (SCE). Final chord length, about 28.9 mm (1.14 in.).

(b) Specimen 38, bent in air to a chord length of about 27.6 mm (1.09 in.) during a period of 24 hr.

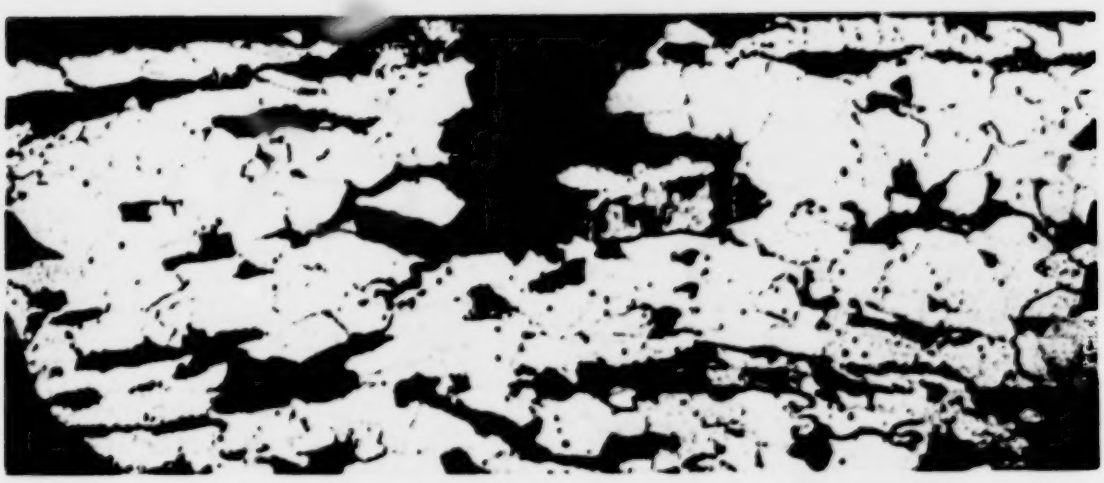


Fig. 11. Section showing SCC in specimen 45, tested in 1 N Na_2CO_3-1 N $NaHCO_3$ at 90°C (195°F) and -0.67 V (SCE) X910

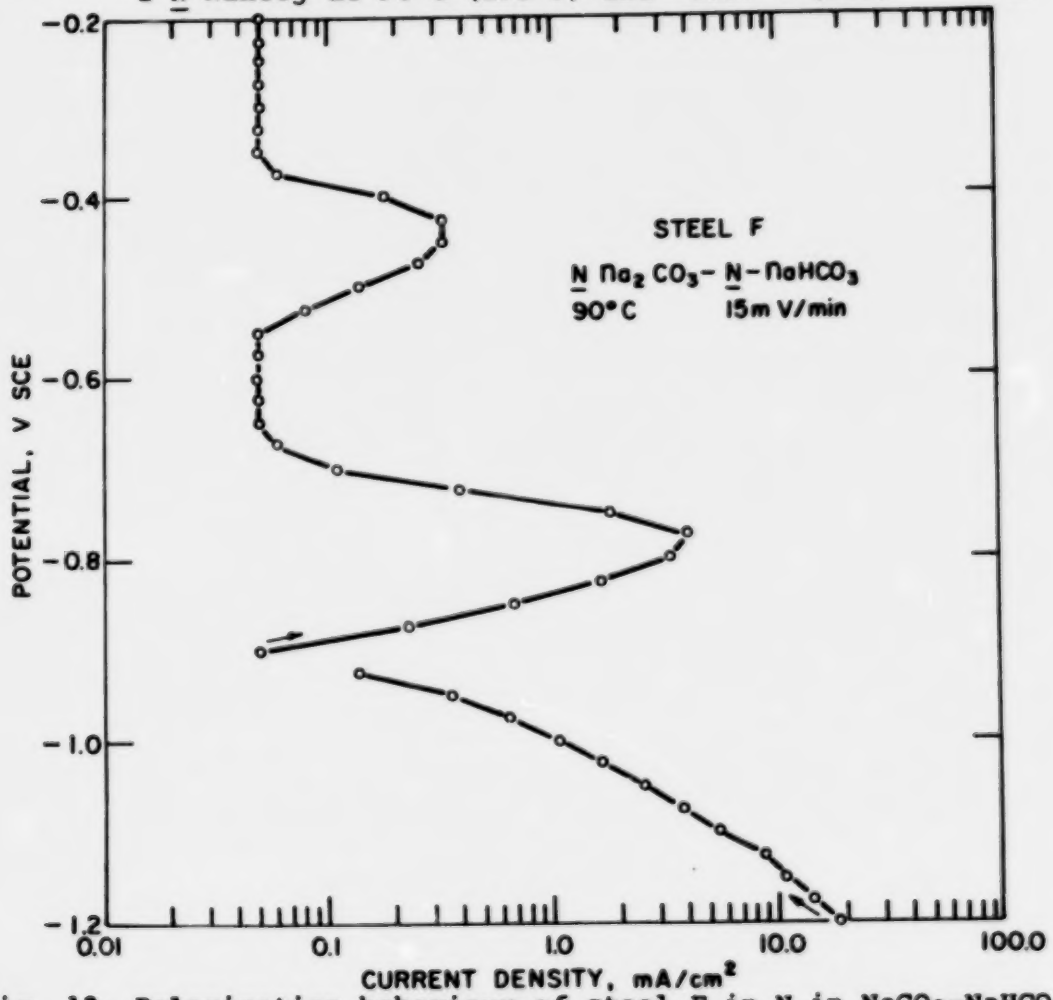


Fig. 12. Polarization behaviour of steel F in N in $NaCO_3$-$NaHCO_3$ solution at 90°C (195°F).

POOR

QUALITY

ORIGINAL